FDTD Analysis of a New Leaky Traveling Wave Antenna†

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Abstract: A new antenna is proposed based on a structure first constructed by Menzel [1] that utilizes the leaky wave phenomena of the first higher order mode. This work seeks to determine the effect on performance of the antenna due to varying geometries. Standard antenna range far-field and near-field measurements are not sensitive enough to extract the propagation constant. A numerical simulation was thus developed using the Finite Difference Time Domain (FDTD) method to extract the propagation constant. The simulation was validated with published analytical data as well as measured data.

Keywords: FDTD, leaky wave antenna, Menzel, microstrip

1. Leaky Wave Antenna Theory

Antennas that operate in a resonance configuration have limited bandwidth due to the destructive interference of the waves. Bandwidth can be increased by blocking the standing wave and instead using a traveling wave. In this configuration, the voltage and current are in phase and have the same $e^{-j\gamma z}$ distribution along the length, where $\gamma = k_z = \beta - j\alpha$. If the cross section is uniform along the length, the H-plane far-field pattern can be estimated by a line source with a current distribution: $I = I_0 e^{-j\gamma z}$. The lower limit of the leaky wave bandwidth is the frequency at which $\alpha = \beta$ and the upper limit occurs when $\beta = k_0$. Small α results in an electrically long aperture giving a narrow beamwidth.

The fundamental mode of microstrip, EH_0, is a bound mode and does not radiate. If the EH_0 mode is blocked, the next higher mode, EH_1, becomes dominant and the structure radiates as a leaky traveling wave antenna. A phase reversal of the electric field inside the substrate at the cross section midpoint allows the field to decouple from the structure.

Higher order modes on microstrip transmission lines can be described as exhibiting three distinct propagation mechanisms: bound wave, surface wave, and leaky wave. These regimes are distinguishable by the directions in which energy is allowed to propagate. Referring to Figure 1, k_x is the propagation constant in the ***x***-direction, k_y in the ***y***-direction, and k_z in the ***z***-direction. Bound waves exhibit a mostly real k_z, while k_x and k_y are complex. This causes waves to propagate in ***z*** and evanesce in ***x*** and ***y***. This regime is associated with propagation above the structure's cutoff frequency for a particular mode, f_c, and is typically the state at which microwave circuits are designed to operate.

Surface waves are supported by the dielectric layer on a ground plate below f_c. These waves exhibit mostly-real k_x and k_z with complex k_y. Waves quickly attenuate in ***y***; therefore, these waves are associated only with the *surface* of the structure.

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As the frequency is lowered to the point where $\beta < k_0$, a leaky wave results from power coupling per unit length from the structure into free space. The leaky wave is characterized by mostly-real k_x, k_y, and k_z allowing propagation in $\boldsymbol{y}$ into free space. Although surface waves are still present, losses in the leaky wave region are mostly due to radiation of energy *leaking* from the microstrip. The lower limit of this leaky regime is the frequency at which $\alpha = \beta$. Below $\alpha = \beta$, the high evanescence of k_z makes the microstrip appear as a reactive load. Thus this region is frequently referred to as the reactive region.

2. A New Leaky Wave Antenna

Figure 1 shows a new antenna designed to operate at the EH_1 mode. It is an evolution of a design by Menzel, as seen in Figure 2. Menzel's design uses slots cut from the microstrip conductor to block the fundamental mode. Oliner [2] mentions that Menzel's 100 mm length is much too short. This antenna would need to be nearly 220 mm at 6.7 GHz for 90% efficiency, which is a typical traveling wave design rule for efficiency.

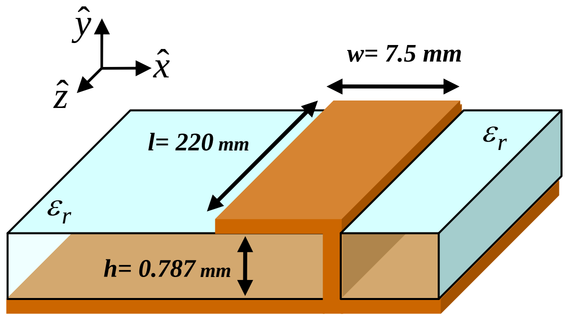


Figure 1: Thiele half width antenna.

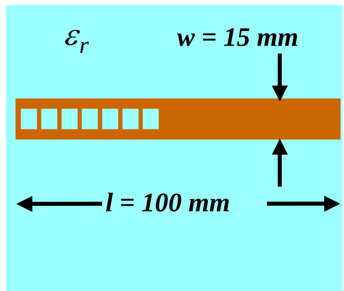


Figure 2: Menzel's original antenna.

The new antenna replaces Menzel's slots with a metal wall down the centerline connecting the conductor strip and the ground plate and should more effectively block the fundamental mode. Due to symmetry and image theory, it is believed that only half of the structure is needed. This new antenna is half of the width of the Menzel antenna. This work shows that the normalized propagation constant generated by the full width antenna is within 0.2% of that generated by the half width antenna, as seen in Figure 4. The bandwidth of Menzel's antenna is reported to be 5.9 - 8.2 GHz. It is hoped that the bandwidth of this design can be improved by varying the height, width, and substrate. FDTD was chosen to model this structure due to the ease of altering the geometry.

Lee [3] analyzed Menzel's antenna with a transverse resonance approximation based on a simplified transmission line model of the cross section, as seen in Figure 3, where $Y_{0\varepsilon}$ is the admittance of the microstrip. The admittance of the end of the microstrip, Y_t, was taken from an approximation derived by Kuester et al [4]. Figure 5 illustrates good agreement between this approximation and the results using FDTD.

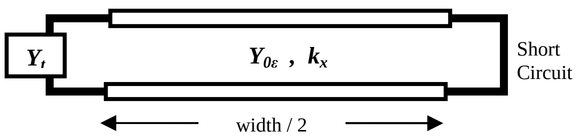


Figure 3: Transverse resonance model of both the Menzel and Thiele antennas.

3. FDTD Simulation

The antenna was excited by giving the E_y component in one or more cells a certain value. This source value was a sinusoid with a cubic ramp over the first three periods. The antenna in Figure 1 was simulated using Matlab over 5.9 - 8.2 GHz, which is the bandwidth predicted by transverse resonance. The 3-D FDTD simulation was patterned after code written by K. Willis and S. Hagness of U. of Wisconsin Computational Electromagnetics Laboratory that used Uniaxial Perfectly Matched Layers (UPML). UPML was not used below the structure's ground plate, since it covered the entire bottom wall of the computational space. Free space was modeled above the substrate layer. All remaining edges of the substrate, as well as the free space above, were terminated with the UPML absorbing layer to isolate only the forward traveling wave. The ground plate and all conductors were modeled as PEC by setting the tangential electric field components to zero for the appropriate cells. The PEC structure was continued into the UPML in both $\boldsymbol{x}$ directions. Since the free space UPML and substrate UPML were in contact, instability was anticipated. By using time steps of no more than 0.9 of the Courant stability bound, no instability was noted after 20,000 time steps.

Computing resources were a limiting factor. The antenna is very thin (< 1 mm) and quite long (up to 1200 mm). Since nearly cubic cells improve FDTD accuracy, this shape creates the need for a huge number of cells. Several tests were run to determine the fewest number of cells needed to accurately model the antenna. The transverse resonance approximation was used as a yard stick to judge the FDTD simulations. The thickness of the UPML layer was found to be frequency dependent. Above 6.7 GHz, only 4 UPML cells proved adequate. Below 6.0 GHz, 16 cells were required. The transition between these points was not linear. The free space region above the antenna was reduced to just 2 cells thick with no noticeable degradation to the results. Likewise, only 2 cells of open substrate on either side of the conducting strip were needed. The tradeoffs between cell size and error were explored. As long as the cross-section dimensions were square, the longitudinal dimension could be five times as long as the cross section size with less than 1% error. The thickness of the substrate was reduced to 5 cells with no measurable effect. The number of cells in the longitudinal direction needed to extract at least two periods of the traveling wave was frequency dependent. The antenna at 5.9 GHz was required to be more than four times longer than the 8.2 GHz antenna. The outcome of these tests was the reduction of the number of cells required to 170,000 at 8.2 GHz and 2,250,000 at 5.9 GHz. This nearly 10-fold decrease in computations and 20-fold decrease in memory allowed all trials above 6.1 GHz to be run on a 3 GHz PC with 1 GB of RAM. The 5.9 - 6.1 GHz trials were run on a 2.5 GHz Mac G5 with 2.5 GB of RAM.

α and β were determined by matching a known $e^{-j\gamma z}$ curve to the E_y field amplitude of the same cross section cell as the source, along the length of the antenna. β was found from a least squares fit of the zero crossings and α was found from a least squares fit of the peak values. As seen in Figure 6, a radiation pattern can be estimated using $\gamma = \beta - j\alpha$ results in $I = I_0 e^{-j\gamma z}$ for a line source.

4. Conclusions

The propagation constant can be used to characterize many performance criteria of a traveling wave antenna, such as bandwidth, main beam direction, and approximate far-field pattern. The propagation constant is vital to the choice of length for an antenna. FDTD is a suitable method of extracting the propagation constant of a microstrip

traveling wave antenna. Through many test cases, the simulation revealed that the antenna could be accurately modeled using only a PC. Thiele's antenna demonstrates that microstrip traveling wave antennas operating on the first higher order mode need only be half the width of recent designs. The simulation is now validated and will be used to predict the effect of altering the geometry of the Thiele half width antenna on bandwidth and radiation pattern.

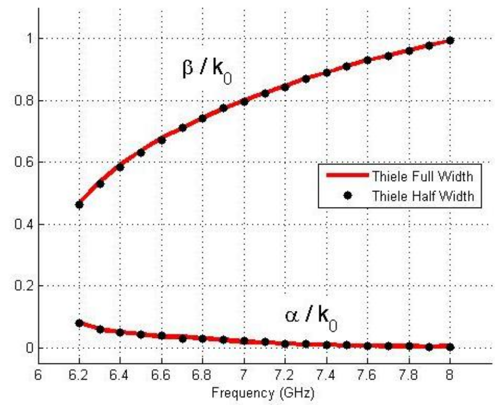


Figure 4: Thiele half width antenna is nearly identical to its full width version.

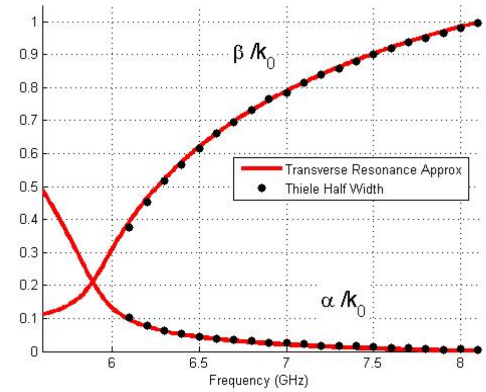
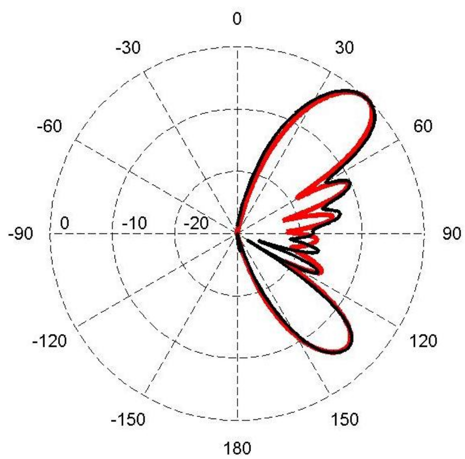


Figure 5: The transverse resonance approximation is simple and reasonably accurate.



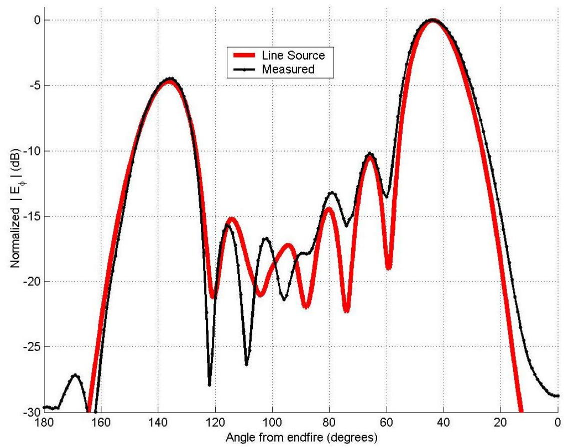


Figure 6: The propagation constant of the measured H-plane radiation pattern of the half width antenna in [5] can be estimated with a best fit of the line source approximation.

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